RISK ASSESSMENT METHODOLOGY FOR RUNWAY END SAFETY AREA (RESA)
AT CANADIAN AIRPORTS

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INTRODUCTION

Accident statistics show that, from 2001 through 2010, 53% of the world's jet aircraft accidents with fatalities occurred during landing and take-off and accounted for 49% of all onboard fatalities (Boeing, 2010). Aircraft overruns, undershoots, and veer-offs account for most of the accidents that occur on or in the immediate vicinity of the runway. Although in many cases the causal factors involve some type of human error, the conditions at the airport can be a significant contributing factor to the severity of the accidents. Based on worldwide data for accidents and incidents collected for the ACRP Report 50 study, from 1982 to 2008 almost 50% of the events that have challenged the RESAs were overruns and undershoots.

RESA is a graded and obstacle-free rectangular-shaped area at the runway end that should be capable, under normal (dry) conditions, of supporting airplanes without causing structural damage to airplanes or injury to their occupants. The rectangular dimensions of the RESA have changed over the years and are dependent on the type and size of aircraft using the runway. To meet aviation continuous growth, airlines are operating larger aircraft with greater seating capacity. However, the configurations of many airports were established many years ago and their RESA configurations and compliance should be re-evaluated.

International community has reasoned that RESAs significantly contribute to the reduction of aircraft damage and passenger injuries. As a result, in 1999, ICAO elevated the RESAs to "standard" under Annex 14 3rd Edition. Canada has lagged behind the international community and as noted in TP312 4th Edition, RESA for runways longer than 1200 m has remained "recommended".

In response to recent domestic and international developments, Transport Canada Civil Aviation (TCCA) published Notice of Proposed Amendment (NPA) 2010-012 to mandate the implementation of RESA at certain certificated airports. This is intended to harmonize the airport requirements for a RESA with the ICAO standards. As proposed in revised NPA, a RESA would be required if the runway is longer than 1200 m or if an instrument runway is utilized by passenger carriers with more than 9 passenger seats.

As a result of industry feedback to the NPA and to better document the risks and safety benefits associated with RESA, TCCA released an RFP for an independent risk assessment study. GENIVAR in combination with Applied Research Associates (ARA) was selected to conduct the study. The main objectives of the study are the following:

(1) Develop a high level qualitative risk assessment model of runway overrun and undershoot

(2) Develop a consequence model for aircraft overrunning and undershooting a runway

(3) Develop a database of certificated airports runways to include major operational characteristics as well as RESA characteristics through surveys

(4) Apply the consequence model to the database both in current RESA condition and in compliant condition.

This paper presents the methodology that is developed for the risk assessment as it is pertinent to takeoff overrun events. Similar methodology can be used for the assessment of the risk for landing overrun and landing undershoot accidents. The risk assessment methodology consists of evaluating the likelihood of a takeoff overrun event based on historic accidents that have happened in Canada and combining that with a consequence model that is also derived from historic events. The paper also presents how the methodology could be implemented to assess the risk of overrun at Canadian airports responding to a questionnaire.

LIKELIHOOD MODELING

To meet the objectives of the project, we are implementing bowtie models. Bowtie method is a risk assessment and management tool used in Oil and Gas industries for decades, and is gaining popularity in aviation industry. The method is very helpful when a big picture of major risk factors are pursued. Bowtie diagrams' logical structures complement the well-known James Reason's Swiss Cheese model and provide a graphical representation of the dependencies between the causes and consequences of the adverse events and the system controls in place. Bowtie is also implemented as a risk management methodology by incorporating mitigations and controls for high risk tasks and procedures, and by assigning responsible individuals and competencies who support and enforce the controls. Among many benefits of bowtie method, ease of communication with key stakeholders, ease of subject matter experts' opinion solicitation and graphical demonstration of probable routes to adverse events are prominent.

The left hand side of the bowties is used for estimating the probability of a takeoff overrun accident. Three risk factors including runway code (1 through 4), aircraft design code (A through F), and the operation types (commercial, private, and government) are considered for modeling the likelihood as shown in Table 1. The commercial operations are further divided according to CARS that separates them further into 701 to 705 classes. Runway code number mainly depends on the length of the runway and aircraft design code is specified by the wing and wheel spans.

The NLR Air Transport Safety Institute of Netherland in conjunction with the FAA led a comprehensive study to construct a causal model for air transport safety (CATS). The study developed event sequence diagrams (ESDs) to illustrate the scenarios that lead up to various modes of failure. The events were categorized broadly so they can encompass a number of events. We are using NLR study estimates as a starting point for likelihood modeling. Only the NLR study ESDs that could result in takeoff overrun are considered for this study. The initiating events of the ESDs as well as the barriers from the NLR study are incorporated into the bowties. Figure 1 below illustrates a schematic of the left hand side of the bowtie in a compact format.

a. Quantification of Left Side of Bowtie

The accident data from the historic events at Canadian airports are being reviewed and assigned to the appropriate categories of the risk factors (runway code, aircraft code and flight category). The causality of the accidents are being identified and accident paths are being constructed by moving through the bowtie and choosing appropriate sequence of events. As a result, the number of accidents passing through all branches of the bowtie will be obtained.

Table 1.
Risk factors for likelihood estimation.

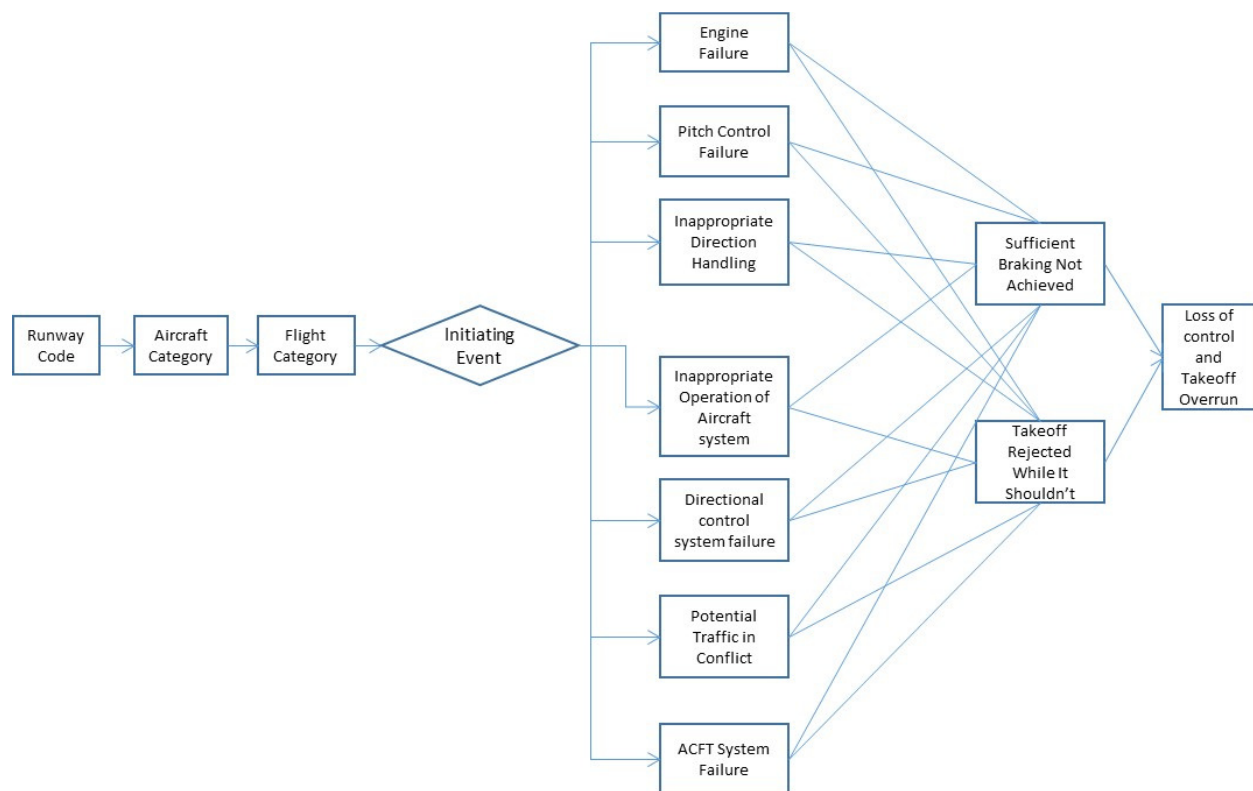| Runway Code (Number)	Aircraft Code	Type of Operation	CARS for Commercial Operations
1	Code A	Commercial	701
2	Code B	Government	702
3	Code C	Private	703
4	Code D	-	704
-	Code E	-	705
-	Code F	-	-

Figure 1. Left side of takeoff overrun bowtie in a compact format.

of accidents passing through all branches of the bowtie will be obtained.

NLR study quantified the likelihood of an overrun based on accidents and operations data from around the world. The quantification is rationale and based on factual data. The assessment encompasses the initiating events through various end results and includes estimates of overrun accidents. We will use the Bayesian method to quantify the likelihood of the accidents for Canada. The NLR estimates will be used as prior estimates in the Bayesian model. The number of takeoff overruns and the total number of takeoff operations in Canada during the

corresponding period establishes the evidence for the Bayesian model. The same technique will be used to update the NLR estimates of the initiating events based on evidence from the historic accidents in Canada.

To establish takeoff overrun frequency (TOORf) ratios, the number of accidents in each of the categories should be divided by the number of operations exposed during the study period (last 20 years). This will result in a three dimensional matrix that includes all the combinations of these frequency ratios as shown in equation 1. The scenarios constructed by StoryBuilder software provide the numerator. We need to obtain the number of operations (or their estimates) over the last 2 decades from the resources that need to be made available to us by Transport Canada to construct the denominator in equation (1).

$$TOORf_{i,j,k} = \frac{(number\ of\ accidents\ in\ last\ 20\ years)_{i,j,k}}{(number\ of\ operations\ in\ last\ 20\ years)_{i,j,k}} \tag{1}$$

where $TOORf_{i,j,k}$ is the takeoff overrun frequency specific to a runway code, aircraft category and operation type; i is the runway code; j is the aircraft code and k is the operation category and each vary according to the Table 1. A multivariate analysis of the risk values will illustrate if the variations in the identified factors (runway code, aircraft code and operation categories) are statistically significant and if it is possible to combine various groups within these factors. As an example, it may be identified that aircraft categories A and B similarly affect the risk, and thus it would be appropriate to combine these categories.

Figure 2 expands the branches shown in Figure 1. Only some of the branches were expanded for illustration purposes. Every accident path goes through one of the branches shown. Starting from the left side, appropriate runway code is first selected from an accident report. Then the aircraft involved in the event is assigned to one of the categories of A to F. In the next step, the type of operation is selected. If the operation type is commercial, appropriate CAR (701 to 705) is selected. In review of the accident report, the initiating event that caused the takeoff overrun is selected from one of the 7 broad categories that encompass the causality of takeoff overruns. For an overrun to happen, either the pilot was unable to achieve sufficient braking to stop the aircraft on the runway after correctly rejecting the takeoff, or the pilot incorrectly rejected the takeoff above V_1. Two accident paths, one in red and the other one in green are shown in the bowtie.

b. Likelihood Assessment of Overrun at Canadian Airports

The frequency ratios obtained from equation (1) will be used to assess the likelihood of takeoff accidents at Canadian airports responding to the questionnaire. For the assessment, the number of takeoffs from each runway of the airport has to be identified according to the aircraft code and the operations category in a given year. The takeoff overrun expected frequency is estimated by multiplying the number of takeoff operations from each aircraft code and operation category and summing over all codes of aircraft and types of operation on a runway for one year as shown below.

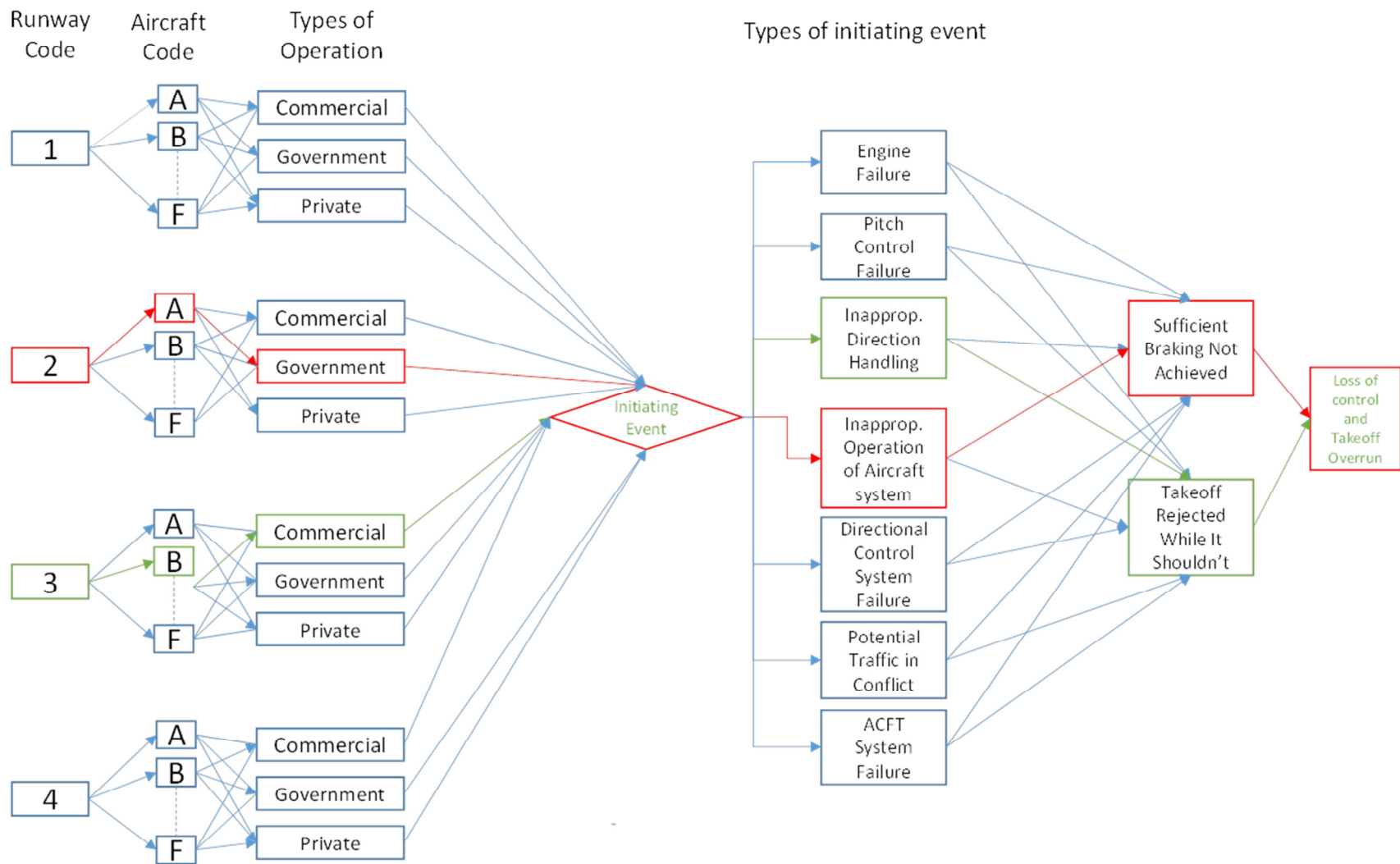$$freq.(TOOR)_i = \sum_j \sum_k \left(TOORf_{i,j,k} \times TO_{j,k} \right) \tag{2}$$

Figure 2. Expansion of risk factors of takeoff overrun for the left side of the bowtie.

where $freq.(TOOR)_i$ is the expected frequency of takeoff overrun in a year obtained for the runway of code i, and $TO_{j,k}$ is the number of takeoffs in category j of aircraft code and category k of operation type.

CONSEQUENCE MODELING

The consequences of takeoff overruns are being assessed in terms of aircraft damage and injuries to the aircraft occupants. The consequences will be modeled using 4 parameters; the aircraft code, the type of the terrain encountered in overrun area, the distance traveled and the obstacles encountered. Table 2 below depicts the categories established for these parameters.

Table 2.
Categories of consequence model parameters.

Aircraft code	Type of Terrain	Distance Traveled	Obstacles
Code A	Paved	0m-30m	Category 1
Code B	Prepared but unpaved	30m-60m	Category 2
Code C	Unprepared	60m-90m	Category 3
Code D	-	90m-120m	Category 4
Code E	-	120m-150m	-
Code F	-	>150m	-

The type of aircraft involved in the accident influences the potential consequences of a takeoff overrun. Type of terrain is assumed to have an effect on the deceleration rate of the overrunning aircraft as well as the potential damages and injuries. A distribution will be constructed based on the distance traveled beyond runway end in 6 intervals as shown in the table. Transport Canada is not anticipated requiring RESAs longer than 150m. Therefore the last distance interval is set for more than 150 m from the runway end.

The last parameter is the obstacle category. The basic idea for the consequence modeling is to assess the effect of different obstacles at various distances from the runway end. The approach integrates the distribution defined by the distance traveled with the location and characteristics of the obstacles at runway ends. The implementation of the approach requires the following simplifying assumptions:

1. The aircraft overrunning the runway will strike the obstacle if the overrunning distance is equal or greater than the distance of the obstacle from the end of the runway. In other words, the size of the obstacle and the wingspan of the aircraft are not considered. This is a conservative assumption since the aircraft may pass from the obstacle and not collide with it.
2. It is assumed that the pilot has no maneuvering control over the aircraft to avoid the collision. This is also a conservative assumption since in some instances the pilots can avoid the collision.

The obstacles are categorized in 4 groups depending on collision speed that may cause hull loss and injuries to the occupants. The groups include the following:

Category 1: Maximum speed is nil

Category 2: Maximum speed is 5 knots

Category 3: Maximum speed is 20 knots

Category 4: Maximum speed is 40 knots

We understand that this is a fairly subjective assignment. However, this is in harmony with the methodology that was developed for the previous ACRP studies. Examples of these obstacle categories are provided in Table 3. This list only serves as a sample and similar conditions must be evaluated in terms of their specific circumstances.

We are using the accident data from the previous ACRP studies as well as the accident data from the Canada for modeling the consequences. Adding events from other countries with similar safety records will enhance the models. The consequences are expected to be similar regardless of the country of accident location.

Table 3.
Sample assignment of obstacles to categories.

Type of Obstacle	Category
Concrete buildings	1
Concrete walls	1
Cliffs	1
Large holes	1
Body of water (undershoot)	1
Stockpiles	1
Highways	1
Flammable material pipeline	1
Gas station	1
Body of water (overrun)	2
Brick wall	2
Non frangible blast fences	2
Large ditches	2
Small ditches	3
Fences	3
Irregular terrain	3
Small depressions	3
Large frangible structures	4
Localizer	4
ALS	4
Frangible blast fences	4
Non prepared areas	4
Lights	no code
Signs (frangible)	no code

a. **Quantification of Right Side of Bowtie**

The right side of the bowtie is shown in Figure 3 in a compact format. The quantification is based on a series of conditional probabilities as the event progresses from left to right. The consequence model consists of two parts; the location model and the outcome model. The location model calculates the probability that the aircraft extends a certain distance beyond the runway end when an overrun has occurred. It is assumed that in a takeoff overrun event, the distance traveled from the end of the runway depends on the type of terrain and the type of aircraft. The outcome model provides the probability of levels of damage to the aircraft and levels of injuries to the aircraft occupants. It is assumed that the damages to the aircraft and the injuries to the people depend on the type of terrain in the overrun area and the category of the obstacle(s) hit during the overrun event. Damages such as blown tires or broken lights are usually referred to as a minor damage while damages requiring engine repairs or broken gears are categorized as major damage. Hull loss damages are typically instances of a major damage to the aircraft body and wings or damages involving multiple engines.
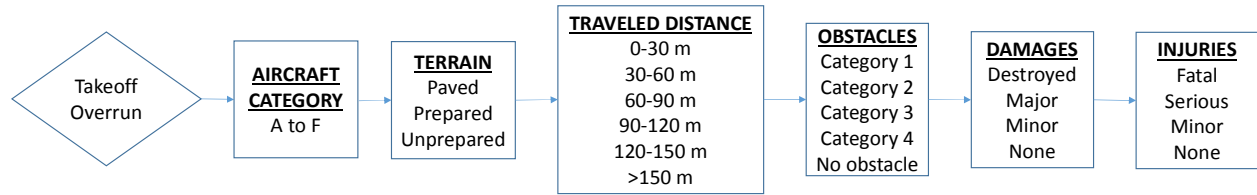

Figure 3. Right side of takeoff overrun bowtie in a compact format.

The multiplication of the location model and the outcome model provides the probability that the aircraft travels certain distance beyond the runway end and endures certain level of damage or injury as a result of encountering certain category of obstacle. This is shown in equations (3.1) and (3.2) below.

$$pr(damage \mid d, obstacle) = pr(d) \times pr(damage \mid obstacle) \qquad (3.1)$$

$$pr(injury \mid d, obstacle) = pr(d) \times pr(injury \mid obstacle) \qquad (3.2)$$

where d is the distance from the end of the runway and is a function of aircraft category and type of terrain. In case there are multiple obstacles in the overrun area, the damage and injury are summed over multiple obstacles as shown in equations (4.1) and (4.2) below.

$$pr(damage \mid multiple\ obstacles) = \sum_i pr(d_i) \times pr(damage_i \mid obstacle_i) \qquad (4.1)$$

$$pr(injury \mid multiple\ obstacles) = \sum_i pr(d_i) \times pr(injury_i \mid obstacle_i) \qquad (4.2)$$

The above equations provide estimates of probabilities for various levels of damage to aircraft and injury to people described in qualitative forms which is normally used in accident reports and investigations. In other words, the equations provide probabilities of minor, major and hull loss damages to aircraft given the obstacles beyond the runway end. Ideally, each level should be translated into a dollar amount, so that the results could be aggregated for all possible

outcomes. However, the dollar amount of damage is rarely available from the accident reports. There are two methods to combine these various effects:

1. One method is to consider only the "worst credible outcome." In doing so, the levels of outcome are sorted from hull loss to major and to minor with their associated probabilities obtained from equations (4.1) and (4.2). Only the most severe outcome whose probability of occurrence is deemed "credible" is elected as the consequence for the risk analysis. The threshold for credibility is a policy decision that should be made by the Transport Canada. This method has been adopted by the FAA for risk assessment in safety management practices in the U.S.

2. The alternative method is to assimilate all levels of damage into one. The benefit of this method is that all levels of outcome, and not just the worst credible one, are accounted for. In doing so, it should be decided how many major damages equate a hull loss, and how many minor damages equate a major damage. The mathematical relationship for this method is shown in equation (5).

$$pr(overall\ damage\ in\ terms\ of\ hull\ loss) = \sum_{i=\text{levels of damage}} \{pr(damage_i) \times \alpha_i\} \qquad (5)$$

where α_i is the multiplier for equating the minor and major damages to the hull loss.

The same two methods can be used for the levels of injuries. Dealing with injuries that include fatality as a potential outcome is more difficult since the evaluation of human life is prone to disputes and philosophical discussions. The above equation can be re-written by replacing the damage with injury and hull loss with fatality.

Figure 3 is expanded to illustrate the sequence of all possible events and consequences as shown in Figure 4. Every accident passes through one of the branches shown similar to the right side of the bowtie. As examples, 2 accident paths are colored in red and green.

b. Consequence Assessment of Overrun at Canadian Airports

To assess the consequence of an overrun for airports responding to the questionnaire, we are obtaining obstacles data at all runway ends in terms of the categories shown in Table 3 as well as their distances from the runway end. In locating the obstacles, only longitudinal distances from the runway ends to the obstacle will be requested from the airports. If an obstacle extends along the longitudinal axis from the runway end, the shortest distance to reach the obstacle will be requested as schematically shown in Figure 3. These are conservative assumptions to facilitate the data reporting for the airports and to simplify the implementation of the methodology.

Airports should also report the types of terrain in 3 major categories within the 150 m distance from the end of the runway. If the overrun terrain is partially paved and partially prepared, the respective lengths should be reported in the questionnaire.

Once the obstacle and terrain data from the airports are obtained, equations (3), (4) and (5) (depending on the method chosen by Transport Canada) will be used to assess the probabilities of the consequences in terms of potential damages and injuries.
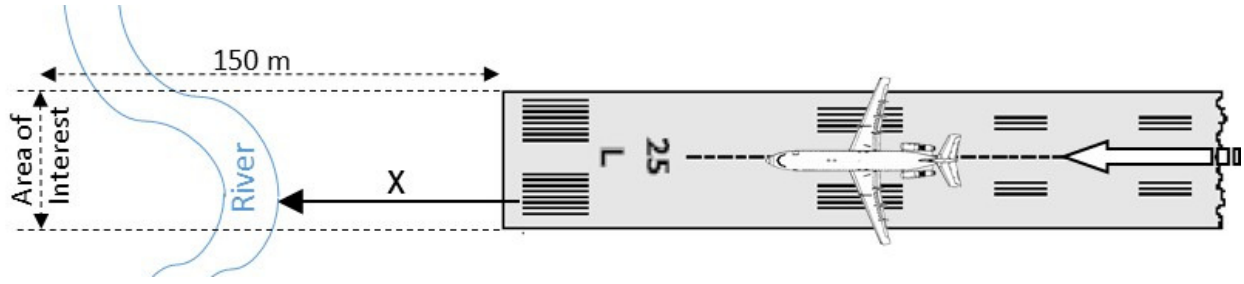
Figure 3. Reporting obstacle distance from runway end.

OVERALL RISK

The risk is the combination of the likelihood of an adverse event and its consequences. To obtain the overall risk of takeoff overrun, the likelihood model and the consequence model are multiplied. The consequence model is presented in 2 dimensions; damages and injuries. Therefore, the risk will be presented with 2 components; risk of damages and risk of injuries. Depending on which method is selected for combining levels of damage and injury, the risks are calculated as shown below by multiplying the takeoff overrun probability by the probability of the highest credible damage or the probability of overall damage.

$$\text{Method 1: } TOOR\ Damage\ Risk = freq.(TOOR) \times pr(worst\ credible\ damage) \tag{6.1}$$

$$\text{Method 2: } TOOR\ Damage\ Risk = freq.(TOOR) \times \sum_{i=\text{levels of damage}} \{pr(damage_i) \times \alpha_i\} \tag{6.2}$$

Similarly for the takeoff overrun injury risk it can be written:

$$\text{Method 1: } TOOR\ Injury\ Risk = freq.(TOOR) \times pr(worst\ credible\ injury) \tag{7.1}$$

$$\text{Method 2: } TOOR\ Injury\ Risk = freq.(TOOR) \times \sum_{i=\text{levels of injury}} \{pr(injury_i) \times \beta_i\} \tag{7.2}$$

where β_i is the multiplier for equating the minor and major injuries to fatality.

Total risk for a runway end is a vector with damage risk and injury risk as its elements as shown in equation (8).

$$Total\ TOOR\ Risk = \{TOOR\ Damage\ Risk,\ TOOR\ Injury\ Risk\} \tag{8}$$

DATA AVAILABILITY

Availability of the data is of paramount importance for the implementation of the risk assessment methodology. Parts of the required data is obtained from the historic accident reports; other parts are expected to be made available to the research team by Transport Canada. To implement the risk methodology at airports, airport operators and owners are expected to provide operation data as required by the methodology through the questionnaire.
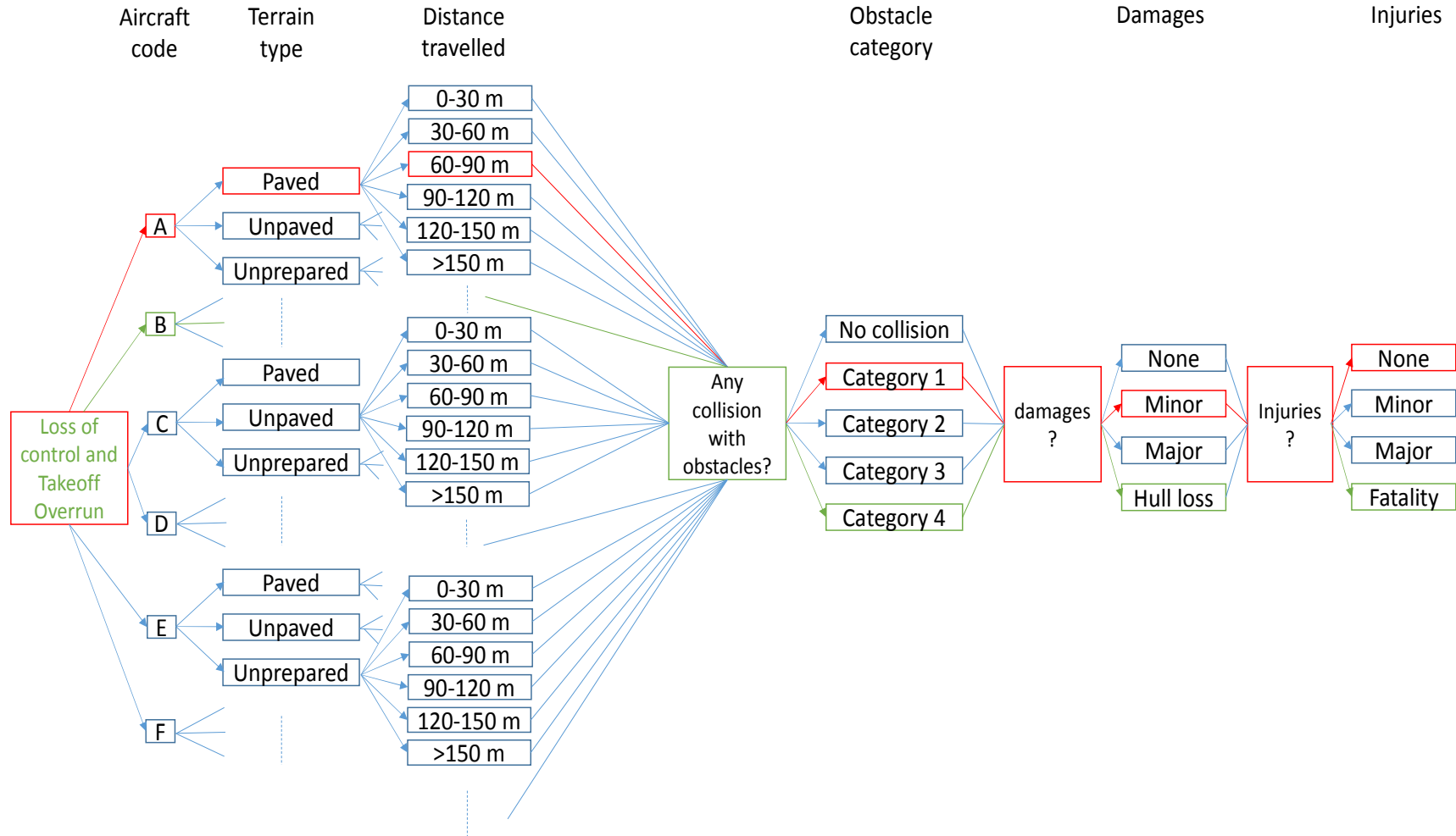
Figure 4. Expansion of events and consequences of takeoff overrun for the right side of the bowtie.

Aircraft accident events are scarce. We anticipate that many of the branches of accidents will not have any historic accidents assigned to them. In other cases, the number of historic accidents assigned to some categories may justify combining them to obtain statistical significance. For example, a great majority of accident data belong to aircraft code A while only a handful of events correspond to other larger aircraft codes. This may obligate combining aircraft codes of larger aircraft types for modeling. As another example, the number of landing undershoot events is a fraction of overrun events. This may warrant combining landing overrun and landing undershoot data to obtain statistical significance for the models.

CONCLUSION

Risk assessment provides a powerful tool for Transport Canada to rationalize the implementation of runway end safety areas at airports. The assessment acknowledges the inherent differences in airport operations and the presence of obstacles at each runway end. The methodology makes it possible to prioritize the improvements at the airports.

ACKNOWLEDGMENT